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Abstract

This paper describes the design of the coil end for the 50mm aperture SSC collider dipole magnets built at Fermilab. The cable paths are determined from both magnetic and mechanical considerations. The end spacers are designed using the developable surface, grouped end approach, which allows the analysis of strain energy within the conductor groups. Techniques for strain energy minimization are presented and the behavior of individual conductors within a group is analyzed. The relationship between optimization of magnetic and mechanical variables is discussed. Requirements of manufacturing and inspection of coil end parts are outlined.

1 Introduction

Fermilab has progressed through many methods of specifying positions of conductors in coil ends [1]. Starting with the outer coil of the SSC 40mm aperture dipole, a method termed ***developable surface/grouped end*** was tried [2]. Analysis of this effort led to the specification that this method be used in the design of the Fermilab-produced SSC 50mm aperture collider dipoles [3]. Each cross section conductor block is treated as a group of conductors that originate at the end of the coil straight section and maintain conductor-to-conductor contact as they wind around and over the coil end. The group is a mathematically determined configuration that attempts to minimize the strain energy of individual conductors within the group and is created by a computer program, BEND, written by Joe Cook [4, 5].

2 Group Definitions

Program BEND interactively accepts group-defining input from the user and constructs a least strain group of conductors in space. The group is defined within a right hand Cartesian coordinate system with a $0,0,0$ origin located on the beam tube center line and the Z-axis coincident to it. The group originates in the X–Y plane at $Z = 0$ and terminates in the Y–Z plane at $X = 0$ where the conductors cross over the beam tube. Thus, only half an as-wound group is defined and is mirrored across the final Y–Z plane for return end groups or matched to different groups for the lead end. The group is constrained in four ways:

- The group's initial direction must be parallel to the positive Z-axis, as is the final direction of the coil straight section from which the group originates.
- The group's initial cross section in the X–Y plane must match the cross section of the straight section of the coil.
- The group's final direction must be parallel to the negative X-axis to provide a continuous curve after X–Y plane mirroring.
- All the conductors in the group are defined to have their radially outermost edges on the outer surface of a cylindrical tube. The outer and inner radii of the tube are the same as the coil outer and inner radii.

The group is constructed around an infinitely thin strip in space called the ***guiding strip*** (see Figure 1). By definition, this is the least strain surface definable within the given constraints. The radially outer edge of the guiding strip lies on the outer surface of the tube and is called the ***base curve***. The radially inner edge of the guiding strip is called the ***free edge***. The free edge is mathematically determined and is not constrained to a tube surface. The ***width*** of the strip is specified by the user and is usually the difference between the outer and inner coil radii.

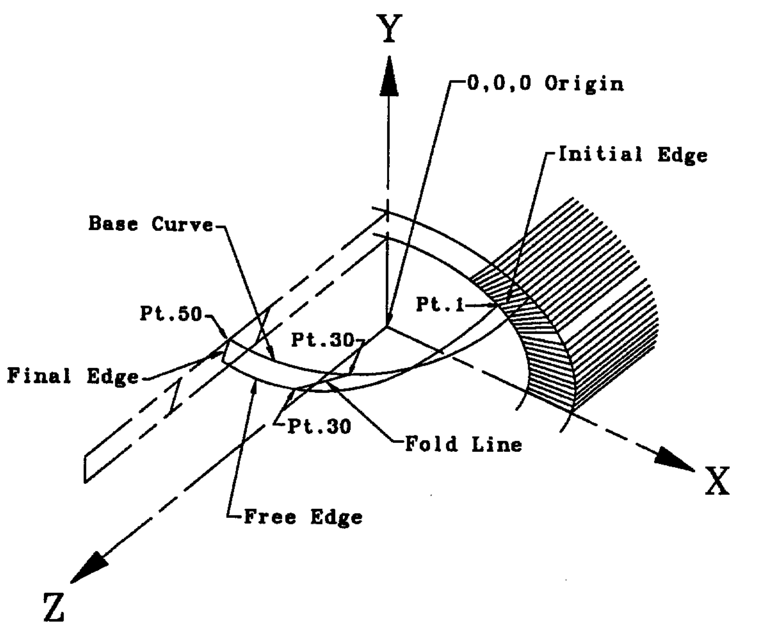

Figure 1. Guiding Strip

Fifty points are established on both the base curve and the free edge. Lines connecting like numbered points on each edge (*e.g.* point 10 to point 10) form a unique set of rulings, or ***fold lines***, which, along with the base curve and free edge, define the surface of the guiding strip.

The guiding strip surface can be located at any conductor surface of the group, including the group-inside and group-outside surfaces. Interactive output from program BEND will refer to all three of these group surfaces (see Figure 2). The number of conductors inside and outside the strip is a user-entered variable set related to the coil cross section and the selected guiding strip position. One-conductor groups to cross between current blocks can be constructed with the guiding strip defined to be on the inside or the outside group surface.

The group is constructed by stacking conductor-size trapezoids against the guiding strip with one trapezoid per conductor per guiding strip point. One edge of the trapezoids adjacent to the guiding strip are coincident to the fold line at that point. The guiding strip fold lines are transferred to the inside and outside group surfaces during this process.

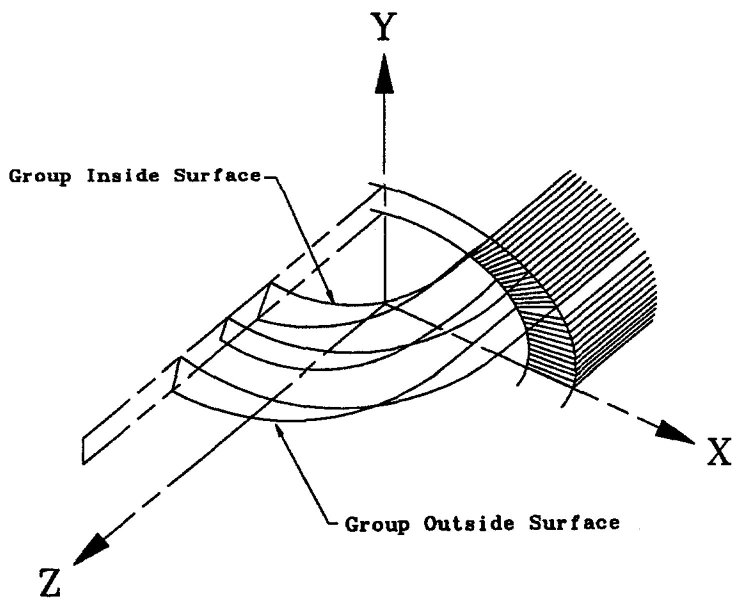

Figure 2. Group Surfaces

3 Group Variables

The edge of a group surface that lies in the initial X–Y plane is called the ***initial edge***, the edge that lies in the final Y–Z plane is called the ***final edge***. The angles from vertical of these two edges are called the ***initial edge angle*** and the ***final edge angle***. The initial edge angle for any group is determined by the coil cross section geometry at the chosen guiding strip location. Refinement of this angle may be necessary to insure that the inside and outside surfaces of the group match the related wedge surfaces in the cross section.

The angle from vertical of a line passing through the $0, 0, 0$ origin and through the intersection of the initial edge and the outer tube radius is called the ***starting angle***. This angle is also determined from the geometry of the coil cross-section. Refinement of this angle on the guiding strip may be necessary to ensure proper azimuthal positioning of the group relative to the cross section.

The user is given the chance to change the distribution of twist along the strip with a variable called ***shift***. A shift of zero is the default value and produces an even distribution of twist. Positive values of shift cause more of the twist to be distributed early in the strip, negative values distribute more twist late in the strip.

Another variable called ***blunt*** changes the radius of curvature of the free edge. A blunt of zero is the default and has no effect on the strip. Positive values of blunt pull the free edge of the strip out near its termination and are used to relieve sharp radii at the nose of the group. Negative values pull the free edge out near its middle and are used to improve areas between groups that may be too thin to support part manufacturing integrity.

The magnitude of the largest Z-coordinate of any group surface is referred to as the ***A-length***. A-lengths are defined only for points that lie on the outer surface of the tube in the final Y–Z plane. Either the guiding strip A-length, the inside group A-length, or the outside group A-length may be specified by the user. This dimension is determined by both magnetic and mechanical considerations.

Magnetically, relative positions of conductor blocks in a coil end can be determined to optimize end field disturbances. A-lengths may be desired to be as small as possible to shorten the magnetic length of the end. An ***origin difference*** may also be applied to a group. The $0, 0, 0$ origin of the group does not have to be coincident to the $0, 0, 0$ origin of the coil end. The origin difference of a group is the distance the X, Y, Z coordinate system of the group is translated along the Z-axis from the $0, 0, 0$ origin of the coil end. A-lengths and origin differences in the end must be specified to provide enough space between conductor groups to adequately support the group.

Certain mechanical considerations may require variation of the desired magnetic configuration. Program BEND distributes the twist in a group in an attempt to minimize the strain energy within the group. An A-length may be too short as specified for a given group to smoothly distribute the group's twist. In some cases, the guiding strip buckles or folds back on itself due to crossing of fold lines. Usually, these conditions will produce a warning in BEND, cause output optimization data to be abnormally high or low, or cause the group to be resistant to attempts at optimization. The user should carefully analyze groups that are hard to optimize.

The magnetic configuration for the SSC 50mm dipole coil ends was determined by Schlomo Caspi and Greg Lee [6]. The outer coil lead and return ends were able to incorporate the A-lengths and origin differences as specified. The inner coil return end also was designed as specified with one exception. The last-wound group had a guiding strip buckling problem that could only be corrected with an increase in A-length. Nearly all the inner coil lead end groups had this problem as well. The origin differences and A-lengths used in the Fermilab design are shown in Figures 3 through 6.

4 Conductor Variables

Conductor ***width*** will be the same as the specified guiding strip width. Conductor ***mid-thickness*** can be the same as the specified compressed, insulated conductor used in the coil. For an exact coil cross section match, the average mid-thickness of the conductors within the group should be used. If a less tightly compressed configuration is desired, ***cable-thickening ratios*** greater than one can be specified that increase the cable mid-thickness at the middle of the group, at the termination of the group, or both. The mid-thickness at the origin of the group will remain unchanged with the specified cable-thickening ratios smoothly applied from there.

The use of the group's average conductor keystone angle will result in exact matching to the appropriate wedge surfaces. Just as the mid-thickness of the conductor can be altered, so can the keystone angle. ***Keystone-widening ratios*** less than one will decrease the conductor keystone angle (without affecting mid-thickness) according to the same constraints as outlined for mid-thickness.

Groups defined for the SSC 40mm magnets used the above conductor modification ratios set to one, specifying the same individual conductor geometry in the end group as found in the coil cross section. Study of these ends showed that the conductor keystone angle appeared to be less in the ends than in the straight section. It also appeared that the group was more tightly compressed at mid-group than at the nose. Based on these observations, keystone-widening ratios of 0.600(mid-group) and 0.700(nose) and cable-thickening ratios of 1.027(mid-group) and 1.000(nose) were used in the SSC 50mm design [7] on both inner and outer coil groups.

Analysis of the first short SSC 50mm ends shows that slightly lower keystone-widening ratios may be an improvement. Inability to close the coil ends to their designed positions without damage to individual conductor insulation has indicated that changes in the cable-thickening ratios are also in order. The specification of larger cable-thickening ratios will result in a coil end that closes to its designed length at the expense of less conductor compaction in the end groups than found in the straight section of the coil.

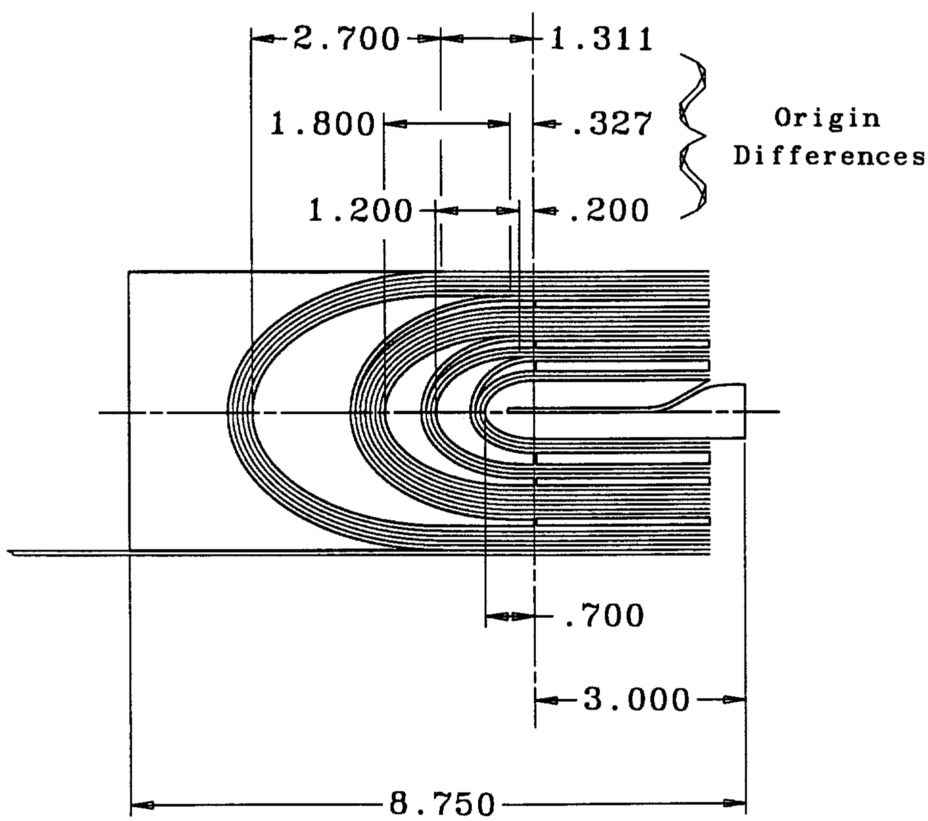

Figure 3. Inner Coil Lead End

5 Group Optimization

The first step towards optimizing a group is a sweep through potential values of shift. Use of the two variables, shift and blunt, will affect the geometry and the strain energy of the guiding strip, negatively in normal groups. However, optimization of these variables can have a pronounced positive effect on the strain energy within the group, particularly on conductors which are farther away from the guiding strip. A non-default value for shift, in particular, can usually be found that produces a least strain group at the specified guiding strip position, with blunt variation saved for problem configurations.

During this interactive process, the user will be able to minimize the $\Delta L/L$, a measure of bend the hard way within the group. If the radius of curvature of the three group surfaces (especially the inside group surface) is considered to be too small, some experimentation with blunt or a change in guiding strip placement may be required. A guiding strip position with fewer conductors inside the strip will sometimes eliminate the problem. Different guiding strip positions can also have a dramatic affect on the $\Delta L/L$ within the group. By empirical analysis, a maximum $\Delta L/L$ of 0.3 and a minimum radius of curvature 2.5mm are considered acceptable limits.

Program BEND also outputs values for strain energies, incremental twist and twist distribution, and a comparative assignment called "badness". The program is in process of being updated to include all these considerations, as well as the torsional and two flexural rigidities of the conductor being used, in an automatic optimization of the group at the specified guiding strip position.

Upon user acceptance of an optimized configuration, BEND offers a chance to save group defining files. These six files will for the most part contain X, Y, Z coordinates of points and will be named by a user-entered file-name and given a three digit file-type:

.COR Contains four corner points for each conductor trapezoid at each fold line. Can be used for mechanical stress analysis.

.CEN Contains the centroid of current for all conductor trapezoids. Can be used for magnetic analysis.

.FRA Contains the Frenet frame for each trapezoid. Can be used to specify automated winding positions.

.INS Contains points defining the inside surface of the group where the fold lines intersect the tube radii.

.OUS Contains points defining the outside surface of the group where the fold lines intersect the tube radii. Also contains points defining the shelf undercut.

.SHF Contains points defining the group's shelf and shelf extension.

6 Part Definitions

The last three BEND output files mentioned above define the boundary surfaces of a group. These files contain fifty X, Y, Z coordinate points for each edge of each surface specified in the file. Coil end parts containing these boundary surfaces are manufactured to constrain the group of conductors to its designed configuration. As on the guiding strip, the points define a unique set of rulings or fold lines that must be contained within all of the various end part surfaces.

Parts used on the return end of a coil are defined by groups which are mirrored across the $Y-Z$ plane. Lead end parts are not symmetrical in this way and must contain group boundary surfaces with both positive and negative X-coordinates. Normally, a return end group is constructed first and used to define half of the corresponding lead end group. New lead end groups are then constructed with the additional requirement of matching the return end group in the final $Y-Z$ plane. Negative signs must be added to the appropriate X-coordinates.

A ten-conductor return end group will typically require a nine-conductor lead end group to match on its inside surface at the final plane and a one-conductor lead end crossover group to match on its outside surface in the final $Y-Z$ plane. The shelf under the lead end group would contain the rearmost surface of the nine-conductor group and the leading surface of the one-conductor group.

As mentioned, the one-conductor group is used to switch the winding from one conductor block to the next. To continue the above example, the filler is defined by the .OUS surface of the nine-conductor lead end group and the .INS surface of the one-conductor group. The one-conductor group should contain approximately the same twist distribution as the nine-conductor group to allow a good fit on the composite shelf used under them.

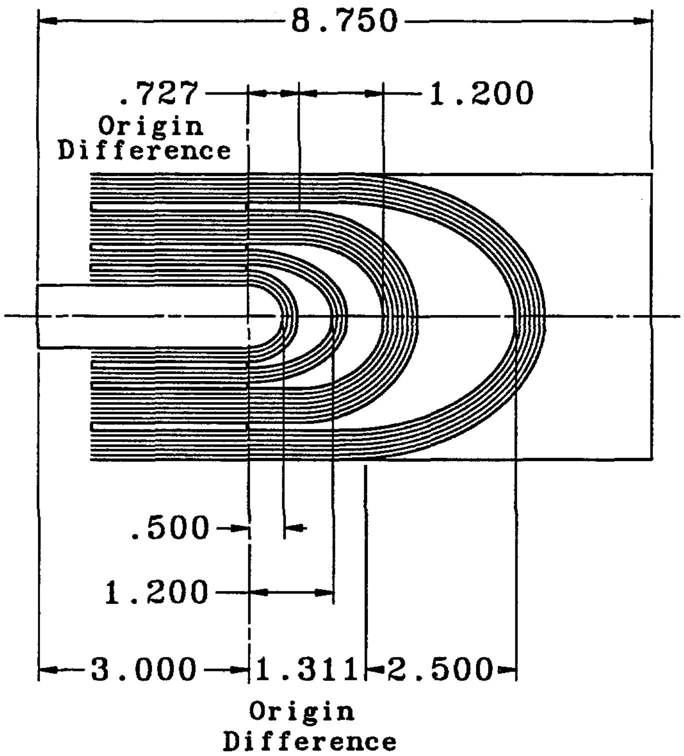

Figure 4. Inner Coil Return End

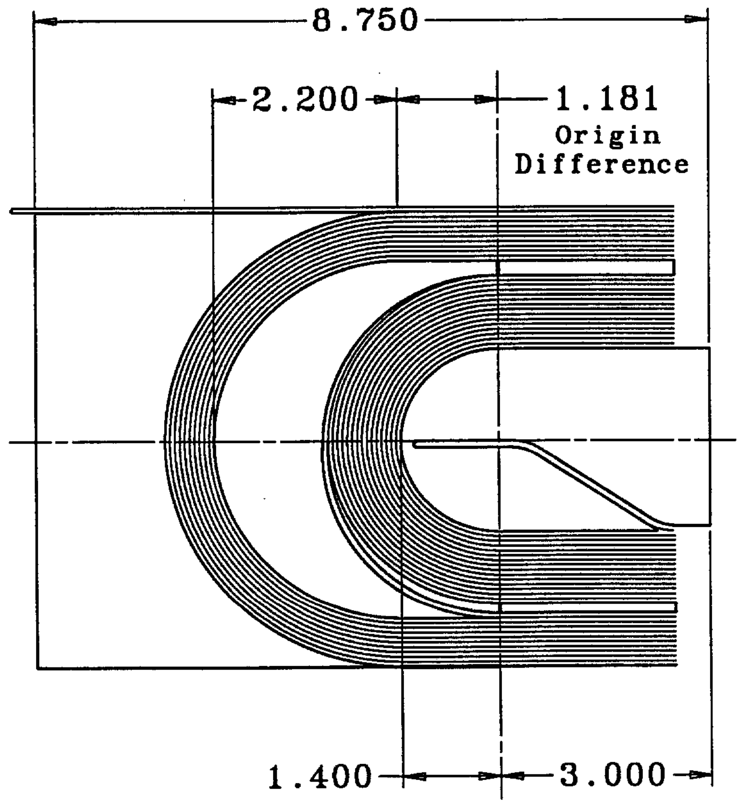

Figure 5. Outer Coil Lead End

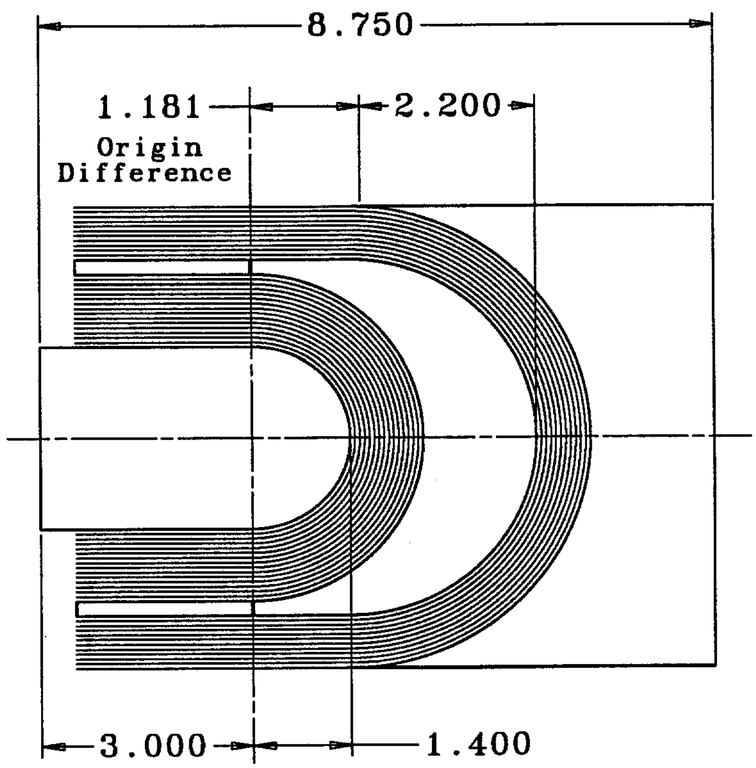

Figure 6. Outer Coil Return End

A computer program called PART has been written by Jeff Brandt that will assemble the necessary group boundary files into coil end part files. The program prompts the user for the group files required to assemble the desired part file and automatically arranges the group files in the required order, adds negative X-coordinates where required and confirms proper lead end group matching. The output from program PART is termed *part data* and is configured to be used as input for other computer programs designed at Fermilab.

7 Part Descriptions

Files defining end parts are assembled from the proper group boundary surface files. The first group in a coil end is wound around a part called a *key*. A key is defined by a group .INS file and may require a shelf to be attached to it. There is one key for each coil end.

A *shelf* is defined for all groups whether it is needed or not. As BEND creates the group, one edge of the conductors are constrained to be coincident to the outside tube surface. If the final edge angles of the group are large enough, the radially inner edges of the conductors will have lifted from the inner tube radius to form a space of varying thickness which is filled by the shelf. The rearmost surface of the shelf is defined by its intersection with the .INS group surface while its leading surface is defined by the shelf's intersection with the .OUS group surface.

The leading surface also has an arbitrary positive Z-axis *extension* applied to it. This extension complicates the shelf but is necessary to prevent uncompressed conductors from overhanging the shelf during the winding process. Overhanging conductors can be damaged in the curing process or can prevent the coil end from closing while being pinched between end parts. The shelf extension requires that the part in front of it be *undercut* to allow the part to slide over the extension during the curing process.

A part called a *spacer* is installed around a previously-wound group and forms the winding surface for the next group. A spacer fills the space between groups and is defined by the .OUS surface of the group behind it and the .INS surface of the group in front. A shelf may be required on a spacer if the group that winds around it requires one, and an undercut may be required on the spacer if the group behind it needs a shelf. A spacer is defined between each conductor group in a coil end.

The spacers for the SSC 50mm dipoles were very stiff by design because of the desire to have a dowel pin through the parts to be used for machining, inspection, and assembly positioning. This stiffness causes problems in the winding process when the spacers are installed around uncompressed groups of conductors. The danger of damaged conductor insulation and the lift of the shelves from the mandrel prevent the spacers from being installed as tightly around the group as they could be. This results in the next-wound group being positioned farther from its desired cured position. All 50mm spacers used at Fermilab are being slotted by a thin saw blade at two or three places on their outer surfaces. These cuts are just deep enough to make the spacers more flexible and easy to correctly position during the winding process.

A part called a *saddle* is installed around the last wound group and provides a surface through which hydraulic pressure to close the end is applied. A saddle may require an undercut if the group behind it needs a shelf. There is one saddle for each coil end.

The final end part type is called a *filler*. A filler is used only on the lead end of the coil to support the one conductor group required in winding to cross between current blocks. There is one filler required for each lead end spacer used in the end.

8 Part Manufacture

Molded end parts are being tested but parts used in the first 50mm coils will be machined from a G-10 tube having the same radii as the coil. Regardless of the method of manufacture, acceptable end parts must contain surfaces based on curves through the part data points and containing the unique set of fold lines generated from connecting like numbered points between the proper curves. If a machine toolpath were defined to cut an end part surface with the side of a cylindrical cutting tool in one pass, so that the tool cut with line contact, fifty of the lines of contact the cutting tool would have as it cut the surface would be the fold lines.

The variation of cutting tool angle required to produce this cut is beyond the limits of some five-axis machines. The integrity of all surfaces must be maintained during the machining of adjacent surfaces. These constraints have forced the machining of most parts to be done in multiple passes, using the end of a cylindrical cutter or the tangent of a spherical cutter in enough passes to produce the specified surface finish and tolerance.

Another machining problem is encountered in trying to maintain part integrity while cutting the many surfaces that feather to zero thickness. These areas are encountered on all shelves, fillers, and lead end spacers, and require special treatment. Cutter size, rotation, depth, feed and speed, as well as part fixturing and hold-down are all variables in successful part manufacturing. Most manufacturers can feather to about 0.13mm before the part material begins to break up due to machining forces.

Shelf extensions and undercuts originate at the curve that is the intersection of the top shelf surface and the outside group surface. Points on this curve are translated in the positive Z direction to a place where the perpendicular length of the extension was approximately 3.18mm all around the shelf. Undercut points were arbitrarily given an additional 0.38mm positive Z direction translation. The fold lines of an extension or an undercut surface consist of rulings parallel to the Z-axis and can be cut with the side of a cylindrical cutter. The corresponding undercut is toleranced to allow for increased Z-axis depth to avoid interference between the tool fillet produced by this cut and the leading surface of the shelf extension.

9 Part Inspection

Some parts have been used at Fermilab that have had shelves produced as a separate piece which was epoxied into a machined notch in the key or spacer it was associated with. This two-piece method was workable but sometimes produced a broken away shelf piece that could be cured in an improper position. One-piece parts have strongly integrated shelves and are desirable for use.

Because the extension of the shelf and the undercut of the part in front of it are defined by the same fold lines, the tolerance on the radial thickness of the shelf and extension is noted as $+0.00$mm/-0.20mm; the corresponding radial tolerance of the undercut is noted as $+0.20$mm/-0.00mm. The tolerance of other conductor contact surfaces is noted as ± 0.20mm with the exception that the tolerance on all surfaces that interface with the coil cross section in the area of the cross section are noted as ± 0.08mm.

A complete set of inspection fixturing has been designed at Fermilab to provide accurate and repeatable 50mm coil end part inspection. This tooling features excellent part positioning and containment and is installed in a measuring apparatus that uses a small spherical probe to contact the part at known nominal point positions. These point positions are produced by a computer program written by John Konc and Greg Lee and are defined to lie on the surface fold lines at the one-fifth, one-half, and four-fifths position of each fold line. The movement of the probe as it checks each part surface is controlled by computer and inspection data is automatically produced. The deviation from nominal of each point checked is recorded and compared to the relevant tolerances specified on the part drawing.

10 Conclusion

The coil end has proven to be one of the most complicated and difficult to define areas of coil design. The developable surface/grouped end approach specified for the SSC 50mm aperture collider dipole magnets has allowed the design of a coil end that is not only the least strain configuration but also provides good placement and containment of each conductor in the cross section. Magnetic and mechanical considerations have been implemented and analyzed and part inspection requirements are fully defined and in place.

References

[1] R. C. Bossert, J. S. Brandt, J. A. Carson, H. J. Fulton, G. C. Lee, "Analytic Solutions to SSC Coil End Design," in *IISSC, Supercollider 1*, M. McAshan, editor, New York: Plenum Press, 1989.

[2] R. C. Bossert, J. M. Cook and J. S. Brandt, *End Designs for Superconducting Magnets*, presented at Breckenridge Workshop, August 14-24, 1989.

[3] R. C. Bossert, J. S. Brandt, J. A. Carson, C. E. Dickey, I. Gonczy, W. A. Koska and J. Strait, "SSC 40mm Short Model Construction Experience," in *Supercollider 2*, M. McAshan, editor, New York: Plenum Press, 1990.

[4] J. M. Cook, "An Application of Differential Geometry to SSC Coil End Design," SSC Laboratory SSCL-N-720, Fermilab TM-1663, Fermi National Accelerator Laboratory, Batavia, IL, 1990.

[5] J. M. Cook, "Strain Energy Minimization in SSC Magnet Winding," in *IEEE Transactions on Magnetics*, vol. 27, pp.1976-1980, March 1991.

[6] S. Caspi and M. Helm, Lawrence Berkeley Laboratory, G. C. Lee, Fermi National Accelerator Laboratory, "A Magnetic End Design of the 5cm SSC Dipole," May 8, 1990.

[7] R. C. Bossert and J. S. Brandt, "SSC End Part Modifications," Fermilab Technical Support Technical Note #TS-SSC 90-042, Fermi National Accelerator Laboratory, Batavia, IL, July 25, 1990.